# On *A*- and *B*-Theoretic Elements of Branching Spacetimes*

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**Abstract**

This paper assesses branching spacetime theories in light of metaphysical considerations concerning time. I present the $A$, $B$, and $C$ series in terms of the temporal structure they impose on sets of events, and raise problems for two elements of extant branching spacetime theories—McCall's 'branch attrition', and the 'no backward branching' feature of Belnap's 'branching space-time'—in terms of their respective $A$- and $B$-theoretic nature. I argue that McCall's presentation of branch attrition can only be coherently formulated on a model with at least two temporal dimensions, and that this results in severing the link between branch attrition and the flow of time. I argue that 'no backward branching' prohibits Belnap's theory from capturing the modal content of indeterministic physical theories, and results in it ascribing to the world a time-asymmetric modal structure that lacks physical justification.

## 1 Introduction

The idea of modeling time as branching features in Arthur Prior's work on tense logic,[1] in which he uses it to provide a suitable semantics for the future tense. Prior's work was itself an attempt to tackle metaphysical issues concerning time, particularly concerning the passage of time, and the 'open future'. Since Prior, branching time has been developed into an axiomatic theory.[2] More recently, branching time semantics have been constructed for relativistic spacetimes in the work of Storrs McCall (1976; 1994) and Nuel Belnap (1992) and have been applied to various contemporary problems in physics, such as the EPR paradox.

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[1] Prior (1967) discussed the concept of branching time within the context of tense logic, following a suggestion from Saul Kripke. See Øhrstrøm et al. (2010) for an account of this episode.

[2] See Belnap et al. (2001).

However, the precise metaphysical commitments of such theories, if any, are not explicit. John Earman's (2008) examination of the topological implications of Belnap's account of branching is the most notable recent consideration of such (meta)physical implications, and his difficulty in assessing whether the type of branching advocated by Belnap is 'ensemble' or 'individual' branching (that is, a collection of histories that diverge over time, or a single spacetime that itself branches), and the response of Placek and Belnap (2010) that it is neither, serve to illustrate the problematic nature of 'interpreting' such theories.

From the perspective of the philosopher of time, such theories are interesting insofar as they touch on such basic and controversial issues as the passage of time, the anisotropy of time, the asymmetry of causation, and the openness of the future. This paper focuses on the metaphysical commitments of branching spacetime theories rather than their logical foundations and corresponding semantics, and specifically on the temporal structure employed by such theories. The first half of my analysis concerns the concept of the 'Moving Now' and its role in McCall's account of branching; the second half concerns the direction of time, and its relation to Belnap's account. I raise problems for both accounts in terms of these respective '$A$-theoretic' and '$B$-theoretic' commitments. Section 2 lays the foundations for the discussion by introducing and explaining the $A$, $B$, and $C$ series, and the corresponding temporal structure they presuppose. Section 3 analyses McCall's 'branch attrition', and argues that it can only be coherently formulated on a model with at least two temporal dimensions, and that this results in severing the link between branch attrition and the flow of time. Section 4 argues that the 'no backward branching' restriction of Belnap's theory prohibits it from capturing the modal content of indeterministic physical theories, and results in it ascribing to the world a time-asymmetric modal structure which lacks physical justification. Section 5 is the conclusion.

# 2 The $A$, $B$, and $C$ Series

## 2.1 McTaggart's Notation

McTaggart (1908) introduced the terms '$A$ series', '$B$ series' and '$C$ series' as different orderings of 'positions' in time. McTaggart describes the $A$ series as "the series of positions running from the far past through the near past to the present, and then from the present to the near future and the far future," and the $B$ series as "the series of positions which runs from earlier to later" (McTaggart, 1908, p. 458). The important distinction between the $A$ and $B$ series is that the former is *dynamic* insofar as what is present, and thus what is past and future, changes over time. For example, the conference at which this paper was presented is past, but while I was preparing my presentation it was future, and at the time of presenting it, it was present. Were I to draw an $A$ series at each of these different times, the different $A$ series would disagree as to which events had which $A$-properties (pastness, presentness, and futurity). The $B$ series is not dynamic in this sense. The preparation of my talk is earlier than the presentation of my talk, and both are earlier than my writing this sentence, and (excluding worries about the openness or non-existence of the future) these $B$-

relations do not change over time—there is no need to 'redraw' the $B$ series at different times. Since McTaggart, it has been commonplace for philosophers of time to classify themselves as either $A$ theorists or $B$ theorists, with the dispute centered on this 'dynamic' quality of the $A$ series, and whether the apparent movement of the present moment towards the future reflects a genuine property of the world over and above our experience of it.

There is a related, but conceptually distinct, question—does time have a privileged direction? This concerns McTaggart's third series, the $C$ series.

> [T]he $C$ series, while it determines the *order*, does not determine the *direction*. If the $C$ series runs M, N, O, P, then the $B$ series from earlier to later cannot run M, O, N, P, or M, P, O, N, or in any way but two. But it can run either M, N, O, P (so that M is earliest and P latest) or else P, O, N, M (so that P is earliest and M latest). And there is nothing [...] in the $C$ series [...] to determine which it will be. (McTaggart, 1908, p. 462, my emphasis.)

It is this distinction between *order* and *direction* that is important in the distinction between the $B$ and $C$ series as I present them. McTaggart's usage of these terms is similar to Reichenbach (1956), and to Max Black's (1959) 'order' and 'arrangement'. Reichenbach and Black use these distinctions to distinguish a directed ordering of events from the bare (undirected) ordering. The $C$ series is clearly contrasted by McTaggart with the $B$ series in terms of its lack of directionality. It is this feature of McTaggart's $C$ series that forms the basis of what I shall call the $C$ series in this paper. The distinction between the $B$ series and the $C$ series is that the $B$ series imposes on events a directionality that is not present in the $C$ series.[3] In this paper I use 'sequence' for directed orderings.

## 2.2 A Structural Hierarchy of Time Series

The $A$, $B$ and $C$ series can be recast in terms of the temporal structure imposed on the sets of events (or times) they contain. Let $x, y$ and $z$ be three events on a timeline, such that $x$ is located at $t_0$, $y$ at $t_1$ and $z$ at $t_2$, and for ease of illustration, stipulate that $y$ is 'present'. Then we can use the following table to represent the respective $A$, $B$, and $C$ series of the events and show the temporal structure contained in each series:

| | Notation | Structure |
|---|---|---|
| $A$ Series | $_{\vec{A}}\{\underline{x}, \boldsymbol{y}, \bar{z}\}$ | Order, direction & distinct event classes |
| $B$ Series | $_{\vec{B}}\{x, y, z\}$ | Order & direction |
| $C$ Series | $_{C}\{x, y, z\}$ | Order |

The $A$, $B$, and $C$ series confer respectively decreasing temporal structure on the events they contain. The $A$ series has a direction (the past-to-future direction) as indicated by the arrow, and distinct classes of members, where underlined text indicates a past event,

[3] McTaggart's concept of the $C$ series in his later writings differs markedly from this brief conception. For example, in McTaggart (1927) the $C$ series plays a central role in McTaggart's neo-Hegelian idealism. McTaggart is also quite clear that he considers the $C$ series not to be a time series. Thus, my $C$ series whilst motivated by McTaggart, is distinct from McTaggart's $C$ series.

boldface indicates a present event, and overlined text indicates a future event. The $B$ series contains no such distinction between its members, but simply an earlier-to-later direction. The $C$ series contains no such directionality, but does impose an ordering on the events, namely a *temporal betweenness* ordering. That is, the $C$ series represented in the table tells us that $y$ is temporally between $x$ and $z$, but tells us no further information[4] as to which is the 'first' or 'last' member.[5]

The three time series differ in terms of their ontological commitments insofar as the $A$ series commits to a 'MOVING NOW', the $B$ series to a primitive directionality of time, and the $C$ series to just a 'temporal betweenness' ordering. This underlies the usage of the terms '$A$-theoretic', '$B$-theoretic', and '$C$-theoretic' in this paper. An $A$-theoretic element of a theory is something that imposes upon the event structure a dynamic partition into past, present and future members. A $B$-theoretic element is something that imposes a structural distinction between the two temporal directions, such as a privileged direction (*i.e.* one of the two temporal directions is the one in which processes 'really' happen). A $C$-theoretic element is anything that confers a betweenness ordering on the event structure. Given the hierarchical nature of the $A$, $B$ and $C$ series it follows that an $A$-theoretic theory has $A$-, $B$- and $C$-theoretic elements, and a $B$-theoretic theory has $B$- and $C$-theoretic elements, but no $A$-theoretic elements, *etc.*

The following two sections concern certain $A$- and $B$-theoretic elements of branching spacetime theories—the $A$-theoretic 'branch attrition' of Storrs McCall, and the $B$-theoretic 'no backward branching' postulate of Nuel Belnap. I will raise problems for both in virtue of their respective $A$- and $B$-theoretic nature.

# 3 *A*-Theoretic Branching

Storrs McCall (1976; 1994) defends an $A$-theoretic branching spacetime model. McCall's model has the feature that at every moment, all but one futurewards branch emanating from that moment fall from the universe tree, resulting in a shrinking future of possibilities, and a growing, determinate past/present. This structure provides McCall's model with a dynamic past/present/future distinction—an $A$ series. The intended advantage of incorporating such $A$-theoretic structure in his model is that it allows McCall to hold both that the past is linear, and thus determinate, and the future is wholly indeterminate, *and* that over time, of all the possible futures, only one is 'actualised'. This allows for both a genuinely indeterminate, open future, and for only one history to ultimately actualise.

In this section I will argue that McCall's model is problematic due to its $A$-theoretic element of branch attrition. Branch attrition is subject to a general criticism of the $A$ series, namely that accommodating both an objective *and dynamic* past/present/future distinction

[4]That is, $_C\{x, y, z\}$ and $_C\{z, y, x\}$ are equivalent insofar as they express the same temporal betweenness relations.

[5]On my usage, $A$, $B$, and $C$ series can, provided the relevant relations hold, be provided for any finite set of timelike separated events. My usage of 'first' and 'last' here is not meant to imply that there must actually be finitely many events.

requires a second temporal dimension. I first introduce what I call '*A* series realism', and argue that it requires a 'two-time framework'. I argue that McCall commits to *A* series realism and thus his model requires the two-time framework. I consider his response to similar objections, and argue that it misses the target. I demonstrate that the incorporation of a second time dimension illuminates the concept of branch attrition and distinguishes it from the flow of time.

## 3.1 *A* Series Realism & the Two-Time Framework

*A* series realism consists of two tenets:

**Objectivity.** There is an objective, non-perspectival, *A* series of events (an objective past/present/future distinction).[6]

**Dynamism.** The *A*-properties of individual events (pastness, presentness, futurity, and related metrical properties) change over time.[7]

The problem for the would-be *A* series realist, as famously demonstrated by McTaggart (1908), is that these tenets pull in opposite directions. Before highlighting the problematic nature of *A* series realism, I will show that McCall's model, and any properly *A*-theoretic branching spacetime model, commits to both tenets of *A* series realism.

McCall (1976; 1994) defends a 'branching Minkowski spacetime', in which individual histories correspond to separate (non-branching) Minkowski spacetimes. The primary concern of McCall is to provide an ontologically indeterministic Lorentz-invariant model, which he attempts to do by presenting a model that, towards the past, is effectively a standard (non-branching) Minkowski spacetime, but towards the future, each 'possible future' corresponds to a separate continuant of the Minkowski spacetime, resulting in a branching pseudo-Minkowskian spacetime. That is, McCall provides his model with an objective past/present/future distinction. The distinguishing, and most clearly *A*-theoretic, feature of McCall's model is 'branch attrition'—the model is dynamic insofar as it loses branches 'over time'.

> Of all the possible futures represented by space-time manifolds which branch off from the first branch point on the model, one and only one becomes 'actual', *i.e.* becomes part of the past. The other branches vanish. The universe model is a tree that 'grows' or ages by losing branches. (McCall, 1994, p. 3)

[6]By 'objective', I mean not merely 'mind-independent'. Rather, for a time to be 'objectively' present, for example, I mean that it is a fact of the four dimensional universe as-a-whole that a particular time is present and all other times non-present. This is to say that the 'presentness' of a time is not merely perspectival, such as a time being present from the perspective of that time, as every time can be present in this way without any one being privileged. Rather, 'objective' presentness is intended to express a fact about the universe from an external perspective (or rather from no perspective whatsoever), and it thus picks out one time as present at the expense of all others.

[7]The adjective 'dynamic' is commonly used in the philosophy of time literature as a converse to 'static'. This usage of 'dynamic' refers to change, and has nothing in particular to do with force, unlike its usage in physics.

Given that on McCall's model 'well-defined regions correspond to past, present, and future' and that, because of branch attrition, 'the borderline between these regions is constantly altering' (McCall, 1994, p. 35), it is clear that it aims at both tenets of $A$ series realism. I shall now clarify these tenets and show why their conjunction is problematic.

### 3.1.1 Objectivity

The first tenet of $A$ series realism is that there is a non-perspectival fact about the universe as-a-whole that a certain time, or class of events, is present, and earlier (later) events are past (future), providing an objective (recall footnote 6) past/present/future distinction. This is over-and-above the claim that, relative to a time, that time is present and that earlier (later) times are past (future). Indeed, McCall explains that, on his model, "there is an objective 'now' whether or not the world contains conscious beings" (McCall, 1998, p. 321), this being the time of the lowest branching point.

It is relatively unproblematic to model an objective past/present/future distinction.[8] Once this is done, take three events—$p$, located at time $t_1$, $q$, located at time $t_2$, and $r$, located at time $t_3$—and stipulate that the Now is located at time $t_2$. Then one can assign $p$ the $A$-property of pastness, $q$ presentness, and $r$ futurity. This may be denoted as an $A$ series as follows:

$$\overrightarrow{A}\{\underline{p}, \boldsymbol{q}, \bar{r}\} \tag{1}$$

### 3.1.2 Dynamism

Combining the two tenets of $A$ series realism is inherently problematic. The second tenet, that the $A$ series is *dynamic*, is perhaps the most salient feature of the $A$ series, at least as initially presented by McTaggart. This is intended to capture the intuition that the present moment is constantly moving towards the future, that future events will become present, and then past. If $p$ is past, $q$ is present, and $r$ is future, then $p$ *was* present, $r$ *will be* present, *etc.* We can see this more clearly using the notation introduced above. For our three events, the following $A$ series hold 'successively':

$$\overrightarrow{A}\{\boldsymbol{p}, \bar{q}, \bar{r}\} \tag{2}$$

$$\overrightarrow{A}\{\underline{p}, \boldsymbol{q}, \bar{r}\} \tag{3}$$

$$\overrightarrow{A}\{\underline{p}, \underline{q}, \boldsymbol{r}\} \tag{4}$$

[8] *e.g.* On Newtonian and neo-Newtonian spacetimes, such a distinction can be achieved by denoting a class of simultaneous events as being 'present', and, relative to a temporal orientation, the class of later events 'future', and the class of earlier events 'past'. On Minkowski spacetime, one can choose a spacelike hypersurface to represent the present moment, and again using a temporal orientation, plus a foliation of spacetime into spacelike hypersurfaces (of which our 'present' hypersurface is a member), define 'the past' and 'the future' as the regions respectively earlier and later than the present hypersurface. Alternatively, one can avoid introducing a foliation of spacetime into spacelike hypersurfaces by making the past/present/future distinction relative to individual point events.

The problem here is that these $A$ series are incompatible insofar as they differ as to the past/present/future distinction of the events, which is, for the $A$ series realist, objective, in the sense explained above. This is, in essence, McTaggart's (in)famous critique of the $A$ series—that pastness, presentness, and futurity are incompatible, and yet each event possesses them all. This is *prima facie* not a problem as we know that these hold 'successively' and not 'simultaneously'. That is, we do not take them all to be *the* $A$ series of the events (*simpliciter*) as this leads to contradiction. Rather, these $A$ series must be indexed. However, the terms 'successively' and 'simultaneously' are in scare quotes because they are ambiguous. How we interpret them depends on *how* we index the $A$ series, and this leads to a problem for the $A$ theorist, with which McCall is faced.

### 3.1.3 The Threat of Perspectivalism

Intuitively, an $A$ series is indexed by time. Consider the different $A$ series of $p$, $q$, and $r$ above. I stated that the sequence runs from (2) to (4). The justification for this is that, for any two timelike separated events $p$ and $q$, $p$ is 'present' *before* $q$ is 'present' iff the time at which $p$ is located is *earlier than* the time at which $q$ is located. From this, the sequence of $A$ series from (2) to (4) follows. This sequence is obvious once we time-index the $A$ series:

$$\underset{A}{\rightarrow}\{\boldsymbol{p}, \bar{q}, \bar{r}\}^{t_1} \tag{5}$$

$$\underset{A}{\rightarrow}\{\underline{p}, \boldsymbol{q}, \bar{r}\}^{t_2} \tag{6}$$

$$\underset{A}{\rightarrow}\{\underline{p}, \underline{q}, \boldsymbol{r}\}^{t_3} \tag{7}$$

However, the time-indexed approach faces the threat of perspectivalism about $A$ series change. On this account, each event is present relative to the time of its occurrence, and past (future) relative to later (earlier) times. This applies equally to every event, and no time is privileged over the rest as objectively present, meaning that every event is past, present and future in exactly the same way—no event has a unique $A$-property. An event is no more a present event than it is a past or future event; whichever it is depends on the time to which one chooses to index one's $A$ series. The apparent dynamism of the $A$ series is simply due to the sequence of times which entails that (*e.g.*) (5) precedes (6). Rather than describing the genuine change of the universe as-a-whole, the time-indexed approach simply provides a sequence of different perspectives of the same universe.[9]

### 3.1.4 The Two-Time Framework

Perspectivalism can be avoided by indexing the $A$ series as follows:

[9] One can similarly construct a series of spatial $A$ series using an indexical 'hereness', holding that each object is 'here' relative to the point at which it is located, and order these $A$ series in the same way as the spatial points are ordered. However, we would not consider this ordering of $A$ series as describing an objective Moving 'Here'. The only major difference between this and the time-indexed $A$ series is that we take time to have a *direction*, thus giving us a sequence of $A$ series rather than just an order of $A$ series, and direction alone is insufficient to add an objective Moving 'Here'/'Now' to the picture.

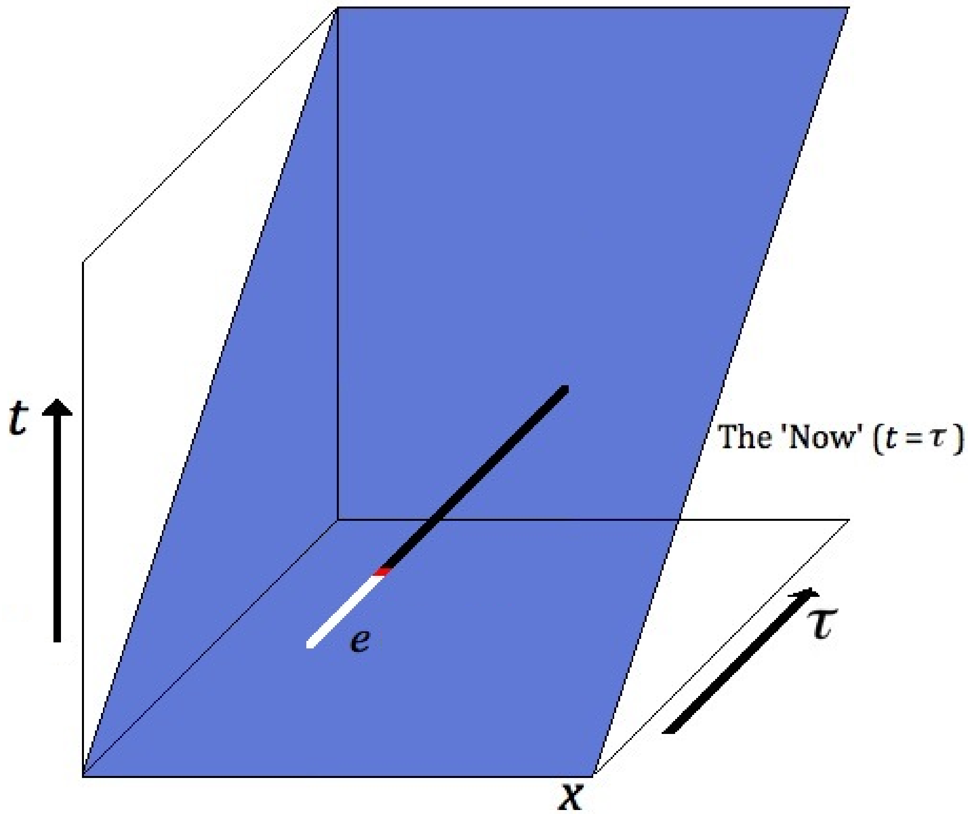



Figure 1: The Two-Time Framework.

$$\overrightarrow{A}\{\boldsymbol{p}, \bar{q}, \bar{r}\}^{\tau_1} \tag{8}$$

$$\overrightarrow{A}\{\underline{p}, \boldsymbol{q}, \bar{r}\}^{\tau_2} \tag{9}$$

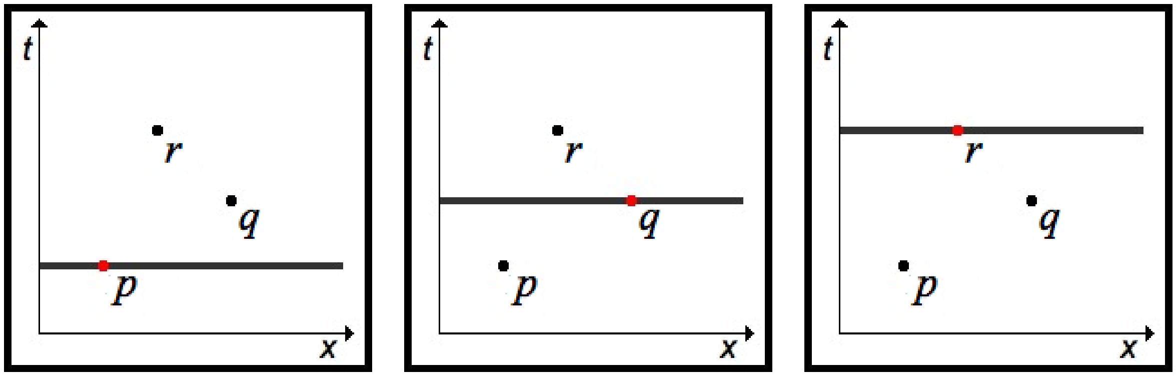
$$\overrightarrow{A}\{\underline{p}, \underline{q}, \boldsymbol{r}\}^{\tau_3} \tag{10}$$

where $\tau_n$ denotes a 'supertemporal' location. The idea is that each of the $A$ series above obtain at successive$_\tau$ supertemporal locations. (I will use $\tau$ as a subscript for ordinary temporal terms when applied to supertime rather than time).

At this point, it is helpful to depict the point I am making. The $A$ series realist is committed to the existence of an objective Moving Now—a privileged present that objectively moves forwards along the time axis. Figure 1 depicts this on a 'two-time framework'. This contains a space axis, $x$, a time axis, $t$, and a supertime axis, $\tau$. The shaded plane represents the (spatially extended[10]) present moment, the Now.[11] By stipulating that there is a

[10]The present is depicted as spatially extended in figure 1 for illustrative reasons only. A suitably relativistic version of such a model would require this to be seen as a frame–dependent representation.

[11]The Now is represented in figure 1 such that it is located at all $(t, \tau)$ where $t = \tau$. This is a coordinate-dependent representation for illustrative purposes. The Now should be understood as a coordinate-




(a) Supertime slice at $\tau_1$ (b) Supertime slice at $\tau_2$ (c) Supertime slice at $\tau_3$

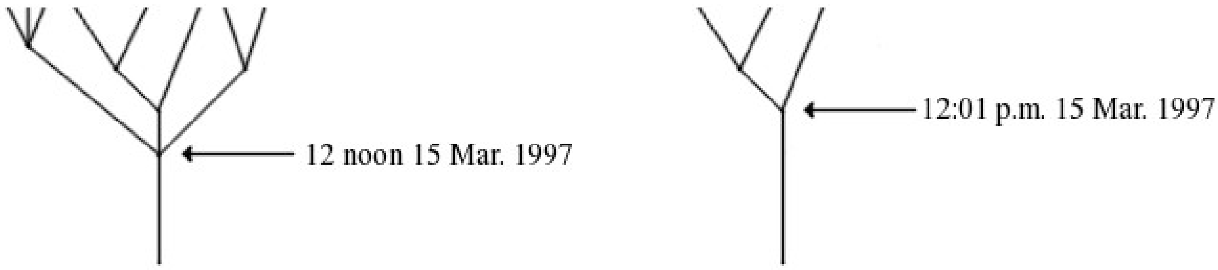
Figure 2: The supertime-indexed $A$ series, where (a), (b) and (c) correspond to (8), (9) and (10) respectively.

privileged direction of supertime, it follows that (8) precedes$_\tau$ (9), *etc.*, thus providing the objective movement of the NOW to later times at later$_\tau$ supertimes. Furthermore, figure 2 depicts 'supertime slices' (that is, a spacetime-at-a-supertime) of the two-time framework, and gives a pictorial representation of (8) to (10). We will shortly return to the two-time framework in the context of McCall's branching spacetime.

The obvious objection is that the two-time framework does not pick out any supertime slice as objectively special, and thus cannot provide an objective past/present/future distinction. However, the two-time framework *does* provide an objective past/present/future distinction. Take an 'event' to be a point with a fully-specified set of space and time coordinates, $(x, y, z, t)$, and thus a point in spacetime. With the introduction of the supertime dimension, we may introduce an different notion, a 'superevent', which is a point with a fully-specified set of space, time, and supertime coordinates, $(x, y, z, t, \tau)$, and thus a point on the two-time framework (where the two-time framework incorporates three spatial dimensions). Figure 1 depicts the event, $e$, located at ($x_2$, $t_1$), extended across the entire $\tau$-axis. Take $e$ to be composed of a set of superevents each with the same $x$ and $t$ coordinates as $e$, but with different $\tau$ coordinates, such that $e$ is just the set $\{e^{\tau_0}, e^{\tau_1}, e^{\tau_2}, \ldots, e^{\tau_n}\}$.[12] Each of these superevents has a unique $A$-property, and thus $e$ is assigned different $A$-properties at different points on the diagram. The white segment of $e$ is where $e$ is future, the red segment is where $e$ is present, and the black segment is where $e$ is past. Thus, the two-time framework provides a contrast between pastness, presentness and futurity that on a one-time framework (a model with a single temporal dimension) is merely a perspectival artefact. It is an objective fact of the universe as-a-whole that (*e.g.*) $e^{\tau_0}$ is future, $e^{\tau_1}$ is present, and $e^{\tau_2}$ is past. However, on a one-time framework, there is no such contrast. For instance, $p$, as modeled in (5) to (7), is not 'objectively' present or non-present; only *from the perspective*

independent structure signifying the region of spacetime at which all and only 'present' superevents are located.

[12]This assumes that supertime is finite in one direction, but this is not essential.




(a) Universe 'at 12 noon.' (b) Universe 'at 12:01 p.m.'

Figure 3: Replication of universe trees from McCall (1994). The universe tree changes from 12 noon to 12:01.

*of* $t_1$ is it present. Only (at least) a *two*-time framework can capture both the objective past/present/future distinction *and* the dynamism of the $A$ series.

## 3.2 Branch Attrition & the Two-Time Framework

I have argued that $A$ series realism requires at least two temporal dimensions, and consequently that if branch attrition is to be taken as an objective process happening to the universe tree, and not as a perspectival artefact in which branches don't objectively disappear from the universe tree, then it requires supertime. I shall now supplement this by showing that McCall's model contains ambiguities and inconsistencies that are removed by incorporating supertime.

### 3.2.1 'When' is 12 noon?

McCall (1994) presents us with two 'universe tree' diagrams, which are replicated in figure 3, and asks us to

> Suppose that the tree at 12 noon on 15 March 1997 has the following shape as in [figure 3a]. Then at 12.01 p.m. it may look like [figure 3b]. (McCall, 1994, p. 3)

But *when* exactly is '12 noon . . . '? McCall's diagram purports to depict a (branching) spacetime, and furthermore the node separating the linear section from the branching section is '12 noon . . . '. By using the arrow to pick out the particular node as being '12 noon . . . ', McCall is indicating that he takes this to single out a point on the time axis of his coordinate system. However, the most we can represent of the world at that time is a *spacelike* hypersurface, *i.e.* a three-dimensional space-at-a-time, and not a four-dimensional space*time*.

McCall also clearly indexes his distinct *trees* by labels such as '12 noon . . . '; he provides distinct *four-dimensional spacetimes* at '12 noon . . . ' and '12:01 . . . '. This shows an ambiguity in his terminology. One the one hand, '12 noon . . . ' is picking out a timeslice of the four-dimensional model, and on the other hand, it is picking out the entire four-dimensional branching spacetime modeled in figure 3a as opposed to that of figure 3b.

In addition to the ambiguity here, neither of the uses of '12 noon ... ' is unproblematic. The use of '12 noon ... ' to pick out a point on figure 3a is problematic as this point also exists on figure 3b, only with different properties; it is a branching point in figure 3a and *not* a branching point in figure 3b (it is simply a point on the line beneath the branching point '12:01 p.m. ... '). Given the incompatible properties of these two points, they are distinct, and thus '12 noon ... ' fails to pick out a particular point. One might think that McCall could respond by appealing to some form of endurantism (he repeatedly refers to the models as being of the 'same world'), but there can be no identity-over-*time* relation here, since the two points are by definition *the same time*. Moreover, there can be no kind of cross-world counterpart relation at play as figures 3a and 3b are meant to be *the same world at different times*. We need more information in order to pick out one of the points; we need to know *which* '12 noon ... ' is being referred to.

### 3.2.2 McCall's Model on the Two-Time Framework

We can model McCall's branching spacetime in terms of the two-time framework, and thus eradicate the ambiguity in his labels by understanding figure 3a and figure 3b as depicting a branching spacetime at different supertimes.[13] That is, figure 3a depicts the model at the supertime at which '12 noon ... ' is *present*. This requires a little elucidating. If we take '12 noon ... ' to refer to a spacelike hypersurface of the spacetime, then we can model our two-time framework relative to the inertial reference frame associated with the foliation of spacetime of which this hypersurface is a member. By doing this, we can, on this coordinate system, refer to this hypersurface as time $t_1$, where $t_1$ represents the *time* '12 noon ... '. Furthermore, we can, using the same convention as before, stipulate that the NOW is located wherever $t = \tau$, and thus state that '12 noon ... ' is 'present' at $(t_1, \tau_1)$. $\tau_1$ is thus the supertime at which '12 noon ... ' is present, and figure 3a, which depicts the model in which '12 noon ... ' is present, is the model at supertime $\tau_1$. Furthermore, if we designate '12:01 ... ' the time coordinate $t_2$, it follows, *mutatis mutandis*, that figure 3b is the model at supertime $\tau_2$.

On the two-time framework we can therefore interpret figures 3a and 3b as depicting a (branching) four-dimensional Minkowski spacetime at different supertimes. We can thus correct McCall's labels as follows. Figure 3a depicts a branching spacetime model at supertime $\tau_1$, the supertime at which '12 noon ... ' is present, and picks out a spacelike hypersurface

[13] My diagram of the two-time framework conflicts with McCall's model in a couple of respects: it is non-branching; and it is not straightforwardly Lorentz-invariant. Moreover, the two-time framework models the passage of spacetime-in-supertime as continuous, whereas McCall's universe-trees are at least depicted discontinuously (branches are either entirely there or not there; they don't gradually fall off). On this point, McCall does present his model as one of a spacetime *continuum*, but the actual process of branch attrition is not itself part of any of the individual universe-trees (this is raised as a problem for McCall by Nerlich (1998)—see 3.3.1 for a discussion of this problem). However, when I talk of understanding McCall's model in terms of the two-time framework, I simply mean that we should understand McCall's universe trees as being separate supertime slices of a branching two-time framework.

of that spacetime, '12 noon ...', which is located at time $t_1$, which is the earliest branching point on that spacetime, thus making it, on McCall's criteria, present, and all points earlier than it past, and all points later than it future. Figure 3b depicts a branching spacetime model at supertime $\tau_2$, the supertime at which '12:01 ...' is present, and picks out a space-like hypersurface of that spacetime, '12:01 ...', which is located at time $t_2$, which is the earliest branching point on that spacetime, thus making it present, and all points earlier than it past, and all points later than it future.

### 3.2.3 The Two-Time Framework achieves McCall's objectives

On the two-time version of McCall's model, there is a branching spacetime that evolves in supertime, which has the following features. For any supertime slice, there is a branching spacetime tree such as those depicted in figures 3a and 3b, in which the trunk represents the past, the lowest branching point represents the present, and the branches represent the future, and thus we have a past/present/future distinction for each four-dimensional spacetime. The past and future directions on the time axis differ structurally insofar as branching only occurs towards the future and not towards the past. If we stipulate that the direction on the supertime axis, with respect to which the present moment moves along the future direction on the time axis, is privileged, then we can form a sequence of supertime slices such that, at later$_\tau$ supertimes, the present moment is located at later times. Thus there is an objective sense in which the NOW moves towards the future.

It follows that the crucial feature of McCall's model, branch attrition, is fully recovered as an objectively meaningful process on the two-time framework. Here, the privileged direction on the supertime axis, coupled with the branching structure of the spacetimes, allows figure 3a to evolve to figure 3b, meaning that, given an appropriate identity-over-supertime relation, the former *becomes*$_\tau$ the latter, and that branches that exist on the former genuinely disappear in the transition to the latter. On this picture, a set of branches emanating from a node located at time $t_1$ is (apart from one member) eliminated in the transition from the supertime slice at $\tau_1$ to the supertime slice at $\tau_2$. Thus, we have a literal, $A$-theoretic account of branch attrition.

## 3.3 McCall's Denial of the Two-Time Framework

The trouble with interpreting McCall's model on the two-time framework is that McCall is quite adamant that his model does not require a second time dimension (McCall 1984; 1994; 1998).[14] However, his argument to this end is somewhat elusive. Consider the following passage.

> An apple tree [...] changes *in* time. But the universe tree, though it changes, does not change *in* time. Rather, its change constitutes the flow of time. Branch attrition, in the model, is what time flow *is*. Therefore branch attrition cannot take place in time, any more than time flow can take place in time. To suppose

[14]The title of McCall (1998) is especially unequivocal in this respect.

> that it can would be to allow that the question, how fast does time flow, makes sense. [...] Change in the universe tree *constitutes* [...] time flow. Time flow is progressive branch attrition. (McCall, 1994, pp. 30-31)

This passage contains some puzzling claims. To start with, McCall, rather than explaining in what sense the universe tree can change, simply states that it does so. However, change is a relative notion. $x$ changes iff it has some property/value that varies with respect to something else; *e.g.* an object can change in temperature with respect to time if its temperature at $t_0$ differs from its temperature at $t_1$; an object can change colour with respect to space if its colour at one point differs from its colour at another point. The idea of primitive, monadic change is highly suspect. The change of the universe tree—branch attrition—is either with respect to some unknown, or is monadic, and thus is somewhat opaque and unsatisfactory.

Nonetheless, McCall argues that branch attrition cannot take place in time for the same reason that time flow cannot take place in time. In what, then, *can* branch attrition take place? I have already argued that in order to model branch attrition, we must use the two-time framework. McCall must show that his account does not require this, but he does not provide an argument to this end. Rather, his only clear objection to the two-time framework is that it allows a meaningful answer to the question of how fast time flows. This is an especially odd objection. If one is to hold that the statement "time is flowing in that direction" is meaningful, then one should not find it *a priori* objectionable for the statement "time is flowing in that direction at such-and-such a rate" to also be meaningful. Leaving to one side the peculiarity of this objection, this passage does not provide an argument towards the contention that McCall's model does not require the two-time framework. On the contrary, the implication of the passage is that on a one-time framework, there is *no* account of the 'change' of the universe, and thus no account of branch attrition.

It is to the strength of the two-time framework version of McCall's model that it *does* provide an articulated account of these features. The universe tree changes insofar as (a) it has different classes of past, present and future events at different supertimes, (b) it has different collections of branches at different supertimes, (c) the present moment has a different temporal coordinate on different supertime slices, and so on. 'Progressive branch attrition' is simply accounted for by the disappearance of branches on later$_\tau$ supertime slices. We also have an objective present moment on each supertime slice that moves to later times at later$_\tau$ supertimes. We also indeed have grounds for declaring "how fast does time flow?" a meaningful question, although as should be clear, the answer is merely a convention—it depends on how we coordinatise the NOW, and it is certainly not clear how this could be an empirical issue. But, contra McCall, this is only a meaningful question inasmuch as "does time flow?" and "in what direction does time flow?" are meaningful questions on the two-time framework, and moreover, a one-time framework contains nothing to provide these questions with meaning.

### 3.3.1 Smart and Nerlich on McCall's Model

The problematic nature of branch attrition has been attacked by Smart (1980; 1995) and Nerlich (1998), with both suggesting that McCall's model requires some sort of extra time dimension. Smart recommends 'hypertime'—which plays much the same role as supertime—and Nerlich recommends 'TIME'—an extra 'time series' required to order the events of branches falling off the universe tree.

Smart's problem is interpretative; he states that McCall's model "is one that I fail to understand" (Smart, 1995, p. 162), suggesting that his own 'Parmenidean' view of time, as opposed to McCall's 'Heraclitean' view, may be responsible for this confusion. In an attempt to make sense of McCall's model, Smart reads it as holding "that there is a super-universe which is like a pack of continuum-many cards, one above the other, cards higher in the pack portraying a longer unbranched 'trunk' than those lower in the pack" (Smart, 1980, p. 7). Smart also suggests to "think of this stack as lying in a five-dimensional space, and call the extra fifth dimension 'hypertime'. Then the tree as it is at a time $t$ would be a 'hypertime slice'" (Smart, 1995, p. 162), indicating that he has something very similar to the two-time framework presentation of McCall's model in mind. However, Smart appears to concede that his difficulty in understanding McCall's model (without the extra time dimension) is not evidence that the model is flawed—"it may be the case that a 'Heraclitean' will find things quite intelligible which are quite obscure to a 'Parmenidean' like me" (Smart, 1980, p. 7). As we have seen, McCall rejects the two-time interpretation of his model. However, his response to Smart is that while the five-dimensional model is a harmless *representation* of the dynamic branching tree, the tree itself is ultimately a four-dimensional object—"Parmenideans may believe that they can 'capture' dynamic objects in static representations, but in the case of branch attrition their price of a second time dimension is just too high to pay" (McCall, 1998, p. 320). This response is particularly strange given that McCall holds 3D 'dynamic' representations of spacetime and 4D 'static' representations of spacetime, to be equivalent noting that they together provide "a nice way of dealing with the problem of identity through time" (McCall, 1998, p. 320).

> The 3D and the 4D conceptions of things are not rivals; they complement each other and jointly throw light on some important philosophical problems. But 3D/4D equivalence is one thing, and 4D/5D equivalence is another. Adding a second time dimension does not resolve philosophical problems, but creates new ones. (McCall, 1998, p. 320)

Contrary to this claim, I have argued that the two-time framework does resolve philosophical problems by using it to clarify ambiguities in McCall's presentation, and using it to model branch attrition, both by appealing to the concept of identity over supertime.

Moreover, there is no good reason to view the two-time framework as 'static' in the sense of providing a Parmenidean, rather than a Heraclitean, picture. Indeed, the term 'static' is of dubious applicability here, since as Price (1996, p. 13) notes, this implies a time frame with respect to which the relevant object, in this case the five-dimensional structure, does not change, but this would require yet another temporal dimension with respect to which the five-dimensional structure were unchanging. As such, the charge that the two-time framework, as I have presented it, is 'static' carries no weight. I have argued that the two-time framework is what is required to support such an $A$-theoretic structure as a MOVING NOW, or indeed, the phenomenon of branch attrition (which, as McCall presents it, either requires or constitutes a MOVING NOW). One may look at figure 1 and see something devoid of Heraclitean flux, but this simply misses the point. Regardless of whether the idea of a primitive 'flow' of time is more substantial than a mere evocative metaphor, my contention is that, on McCall's presentation, branch attrition either requires or constitutes an objective and dynamic past/present/future distinction, and as such requires a model with at least two temporal dimensions.

Nerlich (1998) objects to McCall's model on the grounds that the history of branch attrition—the record of which branches fall off and when—is not obviously contained within the past of the universe tree. Thus, we can distinguish between two different notions of 'the past'. On the one hand, there is the trunk of the universe tree which contains the determinate, actual, temporal past of the spacetime. On the other hand, there is the curious past history of the branching tree itself. As is clear from figure 3, there is a history of branch attrition—at any time, it is the case that there *were* branches that are no longer part of the model.

> The past history of the universe is a sequence of events of branch attrition. Plainly, the unfolding of this sequence is not in the past part of today's tree, else the trunk would be branched. The sequence constitutes another time-series. (Nerlich, 1998, p. 312)

Nerlich terms this extra series 'TIME' and uses it to disambiguate the independent senses in which spatiotemporal events are ordered in time, and branch attrition events are ordered in TIME. This is yet another example of the adoption of an extra time dimension helping to clarify apparent inconsistencies in McCall's presentation.

Extending Nerlich's point, the employment of an extra temporal dimension allows us to distinguish branch attrition from the flow of time. To see that branch attrition is better understood in terms of the 'flow' *of spacetime in supertime*, than in terms of the 'flow' of *time*, one just needs to think the falling of branches as unsychronised. To illustrate, suppose that, on the transition from one supertime slice to the next$_\tau$, several sets of branches fall from different nodes with different temporal locations, such as to prevent the branch structure from giving rise to a clear past/present/future distinction. McCall does not present branch attrition in this way; on his presentation, the branch structure of each tree gives rise to a clear past/present/future distinction. However, consideration of this different kind of branch attrition shows the conceptual distinctness of branch attrition and the MOVING NOW. Here, branch attrition is not correlated with the 'flow' of time, but it *is* correlated with the 'flow' of spacetime in supertime—branches only fall from the tree in the future$_\tau$ direction of supertime. Thus, the project of using the two-time framework to clarify McCall's model and capture branch attrition has the consequence of severing the conceptual link between branch attrition—the change of the spatiotemporal tree in supertime—and time flow—the movement of the NOW towards the temporal future. Whereas the two-time framework is necessary for each of the MOVING NOW and branch attrition, the MOVING NOW can be achieved without branch attrition (as demonstrated in the initial presentation of the two-time framework in §3.1.4), and branch attrition can be achieved without it constituting a MOVING NOW. Therefore, branch attrition is not equivalent to 'time flow' on McCall's usage of the term, undercutting one of McCall's primary motivations, and the central claim of McCall (1976).

## 3.4 Alternative Interpretations of Branch Attrition?

I have argued that an $A$ series realist branching time model requires something akin to the two-time framework in order to achieve its objectives. Whether this commitment serves as a *reductio ad absurdum* against $A$ series realism will not be discussed here.[15] The purpose of this section was highlight the problematic $A$-theoretic nature of branch attrition, and argue that it requires the structure of two time dimensions. As we have seen, the two-time framework clears up certain confusions pertaining to branch attrition, and conceptually distinguishes branch attrition from the MOVING NOW.

There are however alternative interpretations of branch attrition that avoid this commitment, which are worth briefly mentioning. First, one might read branch attrition indexically; *i.e.* at any point on the tree, the other 'possible' continuents of earlier points on the tree 'drop off' merely in an indexical sense. For example, the branch containing the series of events in which I didn't write this paper failed to actualise from my present perspective. However, no branch is privileged—from the perspective of that branch, it is *this* branch that succumbed to branch attrition. (This is, at least in spirit, akin to the $B$-theoretic 'branching space-time' theory of Belnap considered in the next section.) The trouble with this approach, for exactly the same reasons mentioned in consideration of the time-indexed $A$ series, is that branch attrition is not an objective process happening to the universe tree as a whole. It is simply an indexical feature—a perspectival artefact that has no objective correlate. Indeed, due to branch attrition playing a constitutive role in the model's distinction between past, present and future (insofar as the past is the linear section, the present is the first branch point, and the future is the branching section), the past/present/future distinction is consequently not objective. Certainly this account of 'branch attrition' is not properly $A$-theoretic, and as such is outside the intended scope of this section. Moreover, I don't see how this could be the concept that McCall has in mind: firstly, it reduces many of his explicit claims to metaphors; secondly, and crucially, McCall considers it to be a significant virtue of his model that it provides an account of 'objective time flow' (this being the title of his (1976)), and yet

[15] The commitment to multiple time dimensions or time series is often treated as *prima facie* unattractive (*cf.* Smart (1980), McCall (1998)). However, it is too quick to simply dismiss supertime for being counter-intuitive and/or ontologically extravagant. As I have argued, supertime does conceptual work, for instance in making sense of the MOVING NOW. Other instances of the usefulness of supertime are Meiland's (1974) defense of the logical coherence of 'Wellsian' time travel, and Schlesinger's (1980) suggested resolution of McTaggart's paradox. See also Farr (2011) for a consideration of the presentism/eternalism debate in terms of the two-time framework, and for criticisms of supertime.

I have argued in §3.1.3 that this account provides only a perspectival, non-objective account of time flow.

A second interpretation is prompted by the language used by McCall in the following:

> The events contained in each branch which passes through a given branch point are those which are physically possible relative to the set of conditions obtaining at the branch point in question. (McCall, 1994, p. 6)

The idea is that the branching model does not represent the structure of spacetime (or the event structure), but rather represents the 'nomically possible' universe generated by applying the laws governing the time-evolution of the universe (or a subsystem of the universe) to a particular state, or full specification of the dynamical condition of the universe at a time. What is produced can be considered a 'possible universe model' relative to the particular state in question. Note that this idea is perfectly consistent with the universe being 'linear', *i.e.* consistent with there being a perfectly determinate unique 'future' for every event. Based on my reading of McCall, this is not what he has in mind, particularly insofar as this is nomic rather than ontic account of branching—it simply models the nomically possible histories relative to a particular state of the universe, rather than attempting to model how the universe *is*. Furthermore, on this interpretation, branch attrition is again indexical—relative to different states of the universe, there are different classes of nomic branches—and as such is not properly $A$-theoretic.

# 4 $B$-Theoretic Branching

Nuel Belnap's (1992) 'Branching Space-Time' (BST) is a relativity-friendly extension of the theory of branching time (BT), which has generated an active and prosperous recent literature.[16] Unlike McCall's theory, BST contains no $A$-theoretic structure—events are not partitioned into past/present/future classes, nor does BST offer any account of objective temporal passage. As such, BST is not subject to objections concerning the coherence of $A$-theoretic structure. The concern of this section is rather the $B$-theoretic feature that all branching events are *future*-directed. BST is built from a non-empty set of possible point events,[17] $OW$, denoting 'Our World', and an asymmetric, binary, causal ordering relation, $<$, holding between pairs of point events. Although the use of such an asymmetric relation between timelike separated events is $B$-theoretic—it functions as an 'earlier than' relation—it is BST's exclusion of 'backward branching' that I will focus on in this section.

As stated in §2.2, a $B$ theory of time is one that includes a fundamental structural distinction between the two time directions, but lacks a Moving Now (and indeed any objective $A$-properties). However, this does not mean that a $B$ theory necessarily contains a *privileged* direction of time. We may distinguish between a structural distinction between

[16] See the bibliography of Placek and Belnap (2010) for a comprehensive list of recent papers relating to BST.

[17] BST uses point events rather than BT's 'moments' to avoid incompatibility with Minkowski spacetime.

the two temporal directions—temporal *anisotropy*—and one of the two temporal directions being privileged—temporal *unidirectionality.* Temporal unidirectionality is a metaphysical postulate over and above the earlier/later time asymmetry of the $B$ series, insofar as there being distinct earlier and later directions does not entail that either of these is metaphysically special, that either of these is the direction in which processes 'really' evolve.

As in the previous section, I am interested in the metaphysical implications of BST—namely the temporal structure it attributes to the universe if taken metaphysically seriously. However, unlike the previous section, I do not intend to expose any basic flaws concerning the temporal structure of BST. Rather, this section focuses on a particular $B$-theoretic element of BST, its feature of 'no backward branching' (NBB), and BST's consequential exclusion of indeterminism towards an event's past. Although the plausibility of NBB is assumed by Belnap (1992), he acknowledges that "this paper lacks space for discussion of this controversial matter" (Belnap, 1992, p. 389). I argue that due to NBB, BST, as a model of indeterminism, fails to capture a perfectly reasonable and physically-motivated type of indeterminism—namely indeterminism towards the past. I consider and reject the claim that past-indeterminism of physical theories is not relevant to BST as the former, unlike the latter, is not concerned with the modal properties of concrete events. In response, I claim that not only is it reasonable to look to physical theories to provide access to the modal structure of the world, but they are also of more obvious relevance to the study of the (spatio)temporal structure of the world than are intuitions concerning the time asymmetry of agency, which traditionally motivate BT and BST. Finally, I consider reasons, independent of the BST framework, given by defenders of BST for NBB, and argue that they are inconclusive.

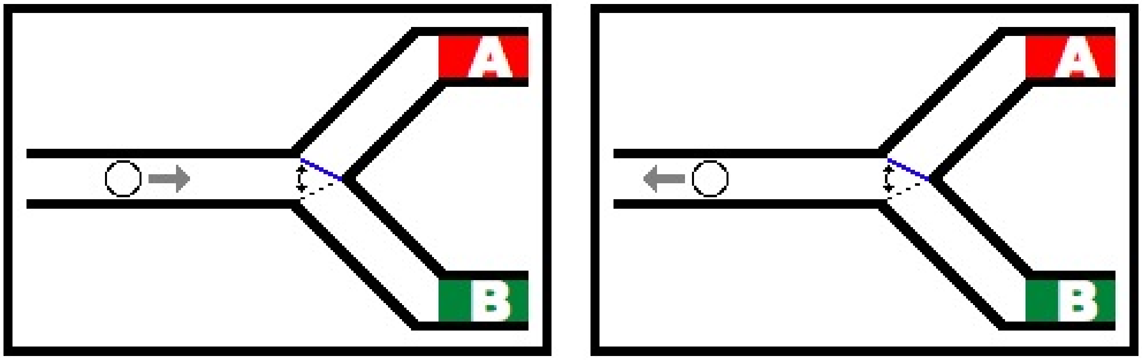
## 4.1 No Backwards Branching

Belnap's (1992) original presentation of BST features NBB as a postulate.

> I am denying that incompatible point events can lie in the past, *i.e.* that some events could have incompatible 'incomes' in the same sense that some have incompatible outcomes. No backward branching is *part of common sense*, including that of scientists when speaking of experiments, measurements, probabilities, some irreversible phenomena, and the like. (Belnap, 1992, pp. 388-9, my emphasis)

The NBB postulate features in standard, non-relativistic, BT semantics (*cf.* Belnap et al. (2001)), and in Belnap's (1992) orginal BST paper. However, it is not strictly required as an additional postulate in BST, since it follows from the Prior Choice Principle along with the the definition of a history as a maximal upper-directed set.[18] Nonetheless, the precise *origin* of the feature of NBB in BST is not of direct relevance to this discussion. The purpose of this section is simply to assess the time-asymmetric restriction on branching imposed by NBB.

[18]Thanks to Alex Malpass and to an anonymous referee for pointing this out.




(a) The ball's future trajectory is indeterministic. (b) The ball's past trajectory is indeterministic.

Figure 4: Future indeterminism and past indeterminism.

## 4.2 Branching and Indeterminism

The notion of indeterminism plays a prominent role in the BT and BST literature. For instance, Belnap presents BST as "a simple blend of relativity and indeterminism" (Belnap, 1992, p. 1). However, due to the forwards-only restriction on branching, BST accommodates only indeterminism towards the future. BST can model an indeterministic future for some event, $e$, insofar as $e$ has multiple future-branches—there are multiple possible futures for $e$. However, due to NBB, each event has a unique past, and as such BST can provide no analogous account of past indeterminism. Indeed, in the context of (non-relativistic) BT, Belnap et al. (2001) stress that "[t]he whole idea of branching time as a theory of indeterminism is that there can be incompatible moments each of which might follow upon a given moment, though there are never incompatible moments in the past" (p. 139).

This restriction immediately appears strong, as there is a simple sense in which the past of a system may be considered to be indeterministic. For instance, figure 4a illustrates a ball travelling at constant velocity towards a gate that can occupy, at any time, either of two positions, each position closing of one of two paths forcing the ball to take the other path. Suppose that the gate switches positions indeterministically, such that given the state depicted, the laws governing the system are compatible with the ball travelling through each of regions A and B (but not both). Thus the future of the ball is nomically indeterministic—according to the laws, the ball will travel through either region A or region B (but not both). Now consider the case where the ball is travelling away from the gate, as in figure 4b. Here, it is the *past* of the ball that is indeterministic. The present state of the system is (by hypothesis) lawlike-compatible with two histories, one in which the ball travelled *via* region A, and one in which the ball travelled *via* region B. Thus, the state depicted in figure 4b has two nomically possible pasts, and as such is intuitively past-indeterministic. The question is how to interpret this kind of past indeterminism. I shall now turn to this issue by comparing the type of indeterminism captured by BST with indeterminism understood in terms of physical laws.

Müller (2009) and Placek and Belnap (2010) each contrast the *modal* concept of indeterminism associated with BST with the model-theoretic analyses of Montague (1974) and Earman (1986) in terms of physical theories, and contend that the concept of (in)determinism is inherently modal. Müller, in particular, is critical of model-theoretic analyses for relegating indeterminism to a property of theories rather than of the world: "first and foremost, determinism and indeterminism are based on real possibility" (p. 49), where "real" possibility refers to in-the-world possibility.

> This [model-theoretic] notion of possibility, being tied to the abstract concept of laws of nature, is [...] too far removed from our initial practical concerns about determinism[, ...which] are not connected with abstract laws, but with concrete situations. (Müller, 2009, pp. 48-49)

There is something of a consensus in the recent BST literature that the discrepancy between modal indeterminism and theory (model-theoretic) indeterminism means that the concept of indeterminism as usually understood by philosophers of physics is incommensurable with that of the indeterminism of BST. This point, in different forms, is made by Belnap et al. (2001), Müller (2009), and Placek and Belnap (2010), to dismiss criticisms of BST's modeling of indeterminism coming from considerations of physical theories. For instance, Placek and Belnap (2010) make this point in response to criticisms of BST by Earman (2008). However, I think this is too quick; consideration of current physical theories does raise genuine problems for the future-only indeterminism of BST. It is perfectly possible to have a modal account of indeterminism that is informed by physics and is time-symmetric. I shall now attempt to demonstrate this by sketching a modal account of indeterminism in terms of physical laws.

#### 4.2.1 Physical (In)determinism

Take a universe, $U$, a set of laws that govern the temporal evolution[19] of $U$, $L^U$, a set of 'instantaneous' states (*i.e.* Cauchy surfaces[20]) of that universe, $S^U$, and a set of 'possible universe histories' that satisfy $L^U$, $H^{L^U}$.

**Physical Determinism.** $U$ is deterministic iff for any state $s \in S^U$, there is exactly one history $h \in H^{L^U}$ such that $s \in h$.

**Physical Indeterminism.** $U$ is indeterministic iff for a state $s \in S^U$, there are at least two histories $h_1, h_2 \in H^{L^U}$ such that $s \in h_1$ & $s \in h_2$, and $h_1 \neq h_2$.

The former says that the universe is deterministic if and only if each instantaneous state of the universe is lawlike compatible with only one universe history, and the latter says a

[19] What I have in mind is more or less what Maudlin (2007) calls 'fundamental laws of temporal evolution', or FLOTEs. The account that follows assumes that there are such things for the sake of discussion. See (Maudlin, 2007, ch. 1) for an articulate and persuasive defense of FLOTEs and their application to the issue of (in)determinism and the analysis of counterfactuals.

[20] A Cauchy surface is a spacelike plane that intersects each inextendible non-spacelike curve exactly once. The data contained on a Cauchy surface thus effectively gives the descriptive state of a system at a time.

universe is indeterministic if and only if an instantaneous state of the universe is lawlike compatible with at least two distinct universe histories. These toy definitions are along the same lines as Montague (1974) and Earman (1986) insofar as they concern laws and world-models satisfying these laws. However, the notion of 'physical possibility' employed is modal—if our world is governed by indeterministic laws, then different past or future states of affairs that are consistent with our present state of affairs are 'physically possible' in the sense that such possibility is a feature of the world, and not an artefact of some theory.

Physical (In)determinism is devoid of $B$-theoretic terms (*e.g.* earlier/later, before/after). It is common, and intuitive, to cast determinism along the lines of "for two models that agree *up to a particular time*, they agree for all times," however, this crucially smuggles in time-asymmetric language. This time asymmetry is not present in Physical Indeterminism because it holds that (in)determinism concerns the relation between an *instantaneous state* and the histories nomologically compatible with it. Thus, the relevant information is contained within the state, and not the state *plus* the past of the state. Denying this is problematic: if one holds, for example, that the future evolution of a system can be affected by information in the past that is not contained within the present state, then one is committed to temporal non-locality—that there can be a 'causal' connection between two states at different times that is not mediated by intermediate states. This is a quite peculiar metaphysic to which to be committed, as it implies that information can in some sense jump discontinuously from one point in time to another, such that it can be 'lost' at some intermediate time, and reappear at another time. However, if we reject such a principle, we are committed to all relevant data being contained in the 'instantaneous' state, and it follows from this that any mention of past or future in the definition of (in)determinism is superfluous and thus misleading.

A universe can be Physically Indeterministic in the case that some state, $s$, is on two possible universe histories that diverge only to (what we would call) the past of $s$, as in figure 4b.[21] Due to NBB, such a universe cannot be BST-indeterministic towards the past.

### 4.2.2 Events, States, and Modality

It may be objected that my discussion of past indeterminism is inapplicable to BST due to my use of 'states' rather than 'events'. For instance, Placek and Belnap stress that "BT/BST concern *events*, not states, and in general both theories are silent about the latter notion" (Placek and Belnap, 2010, §4.4). Likewise, Belnap et al. (2001) holds that the distinction between events and states is crucial, and that the philosopher of physics is missing something when quantifying over states rather than events when speaking of indeterminism:

> [N]o backward branching fails to apply to "states" or other repeatable carriers of partial information. There is no doubt whatsoever that a present "state" may be accessible from either of two earlier incompatible states. There is no doubt about

[21] Montague uses the term 'historical indeterminism' for such issues, as opposed to 'future indeterminism', and holds that "a theory is (simply) *deterministic* if it is both futuristically and historically deterministic, that is, if the determination of states proceeds in both temporal directions" (Montague, 1974, p. 321).

> this because there are so very many senses to the word "state." [...] None of this, however, is relevant to our postulate of no backward branching. To discuss any of it is to change the topic. (Belnap et al., 2001, pp. 184)

Without wishing to change the topic, the problem here, as Belnap et al. note, is the ambiguity of the word 'state'. NBB can be considered to be consistent with past indeterminism if this amounts to the claim that the same descriptive state of the universe—a complete set of magnitudes of the relevant physical observables at a time—can occur on histories that diverge towards the past.

> There is [...] no trouble [for BST] in there being two histories, each containing an interval of events, with the same sequence of states assigned, but each preceded by an event with a different state. (Placek and Belnap, 2010, §4.4)[22]

Events in BST models are event-tokens. They are "concrete particulars" (Placek and Müller, 2007, p. 181) which are "not repeatable" (Placek and Belnap, 2010, §4.4), and hence have a non-qualitative, indexical nature (they are referred to by ostension and not by qualitative description). This understanding of 'event' differs importantly from state-*types*, where a state-type is a complete set of values of the physical observables of a system. However, Physical Indeterminism is not concerned only with state-types, but importantly also with state-tokens. A state-token is a particular, concrete, non-repeatable instance of a physical system being in some state-type; a state-token is effectively a concrete timeslice of a universe. Where event-tokens differ from state-tokens is that state-tokens are non-local (spacelike) maximal regions of a system (*e.g.* a universe) at a time, whereas event-tokens are local regions/points of a spacetime. A state-token can be considered to be an aggregate of all (point) event-tokens at a time. Thus, the 'states' of Physical Indeterminism differ from the 'events' of BST with respect to locality/non-locality, but not with respect to concreteness/abstractness or repeatability/non-repeatability.

To clarify: Physical Indeterminism includes universe laws, $L^U$, as a primitive feature of the universe under consideration; $U$ is a concrete universe; $S^U$ is a complete set of state-*tokens* of $U$ (either a complete 'linear' universe, or one of a branching ensemble of histories[23]); $H^{L^U}$ is the set of models of the laws—where each model is a history of state-*types* that satisfies $L^U$. Since we're not discussing $A$-theoretic structure here, then each time slice of a universe is considered 'equally real', and hence $S^U$ can be understood as the set of all state-tokens that the universe will 'ever' possess. If a state-token of $U$, $s$, corresponds to a state-type that falls on more than one member of $H^{L^U}$, then $s$ has more than one *physically possible* history, and thus in the concrete world, $U$, there are physically indeterministic state transitions—genuinely chancy evolutions. This chanciness is 'out there'—it is a feature of the nomic relations which, by hypothesis, are real physical features of the universe.

If I were to say "a state-type has multiple possible pasts," then I would simply mean that the same set of conditions can occur on histories with distinct pasts. This appears to be the

[22] The usage of 'state' in this passage refers to the concept of state as used in 'Minkowskian Branching Structures' (*cf.* Wronski and Placek (2009)).

[23] That is, a 'universe' can refer to a subset of a branching ensemble of histories.

implication of Belnap et al. and of Placek and Belnap in the above passages when discussing 'states'. However, were I to say "a state-*token* has multiple possible pasts," then I would be saying that a particular, concrete state has multiple, modally incompatible past histories.

Given that a state-token incorporates event-tokens (*e.g. this* state-token of the universe includes *this* event-token of you reading this sentence), then for any state-token, $s$, that has multiple possible pasts, if at least two of these possible pasts differ as to at least one event in the backwards lightcone of some event-token, $e$, where $e$ is included in $s$, then $e$ has multiple possible, modally incompatible pasts. If such modal incompatibility is equivalent to branching (as adherents of BST take it to be in the case that it is future-directed) then it is ruled out by NBB. I shall now consider the justification for such a time-asymmetric restriction on the modal structure of the world. I have already suggested that past indeterminism is at least intuitively plausible. Next, I argue that if we are to justify the metaphysical claim that the universe branches, we must look to physics, and that there are no good reasons to think that such consideration favours the future-only branching of BST.

## 4.3 Physical Modality

If we are to hold that the world has an objective modal structure, as is claimed by adherents of BST, then it is reasonable to look to physics to provide epistemic access to this. Our physical theories deal with modalities—for instance, they are capable of supporting counterfactuals—and the novel predictive success of scientific theories gives us reason to suppose that they succeed in capturing to some degree the modal structure of the world.[24] In introducing Physical Determinism and Physical Indeterminism, I supposed for the sake of discussion that there are primitive laws of nature that dictate the physically possible histories for a given state. To see that this account is indeed modal, consider the case that such laws are deterministic. In this case, if a particular state-token of the universe were to be replaced with a qualitatively distinct state-token, then in order for the universe to remain a solution to the laws (which, given the stipulation that it is a universe with primitive laws of nature, it must) then this effects a change in all state-tokens in the universe. As such, the laws support counterfactuals of the kind "if $x$ had been different than it actually is, then $y$ would have been different than it actually is"[25] and as such are modal.

Although Müller (2009) and Placek and Belnap (2010) emphasise that indeterminism is to be understood as a modal notion, the kind of modal indeterminism that they endorse—BST indeterminism—is importantly an *ontic* notion of indeterminism, in that indeterminism pertains to the modal status of particular existing events. It is this that distinguishes it from Physical Indeterminism, which is a *nomic* account—it locates modality in the laws of

[24]Indeed, this is the central claim of ontic structural realism—*cf.* (Ladyman and Ross, 2007, ch. 3). See also Ladyman (2000) and Maudlin (2007) for discussions of objective modality and physics.

[25](Maudlin, 2007, ch. 1) provides an analysis of counterfactuals in terms of fundamental laws of temporal evolution. Maudlin's analysis however is temporally unidirectional—he uses the laws only to evolve *forwards* in time from the contrary-to-fact antecedent state, thus accounting only for foretracking counterfactuals. See Farr and Reutlinger (2011) for a temporally adirectional account, along these lines, that accounts for both foretracking and backtracking counterfactuals.

temporal evolution. On both accounts indeterminism is a modal notion—indeterminism is a property of the world, not a property of theories as in the model-theoretic accounts. The point I wish to stress is that it does not follow from indeterminism being understood modally that it contains any important time asymmetry to support something like NBB.

On the supposition that physical science provides our primary epistemic access to the physical world, then nomic indeterminism would appear to be prior to ontic indeterminism, understood in terms of branching. A physical theory may dictate that it is nomically indeterministic as to whether there will be a sea battle tomorrow. However, that there exist two modally incompatible real events located tomorrow—a sea battle and the absence of a sea battle—will not be dictated by a physical theory. Indeed, this Aristotelian intuition of an ontologically open future is central to the BT and BST concepts of indeterminism—for instance, Müller holds that "[r]eal possibilities are nothing spooky or special, we live in a world full of them. This world we picture, at least intuitively, as a branching arrangement of possible histories" (Müller, 2009, p. 50). Likewise, Belnap et al. (2001) motivate the semantics of BT and BST in terms of the concept of agency, and hence with basic intuitions concerning our ability to interact with the world, with the inevitable time-asymmetric associations (that we can affect the future and not the past, that it is worth preparing for the future, *etc.*). The worry is that although such intuitions are harmless in providing semantics for everyday scenarios, they are not appropriate when it comes to assessing the fundamental (spatiotemporal) structure of the world, and as such, the role of NBB in BST in particular places a constraint on the structure of spacetime that is not directly motivated by physics.

My contention is that if the laws governing the dynamical evolution of the universe are deterministic—that there is only one physically possible history associated with each state of the universe—then there are insufficient grounds for holding that the universe literally has a branching structure. However, it does not follow from nomic indeterminism that the universe possesses a branching structure. If the state at time $t_0$, $s(t_0)$, coupled with the relevant dynamical laws, fails to uniquely determine the state at $t_1$, it does not follow that there is no unique, determinate state of the system at $t_1$. It only follows that the state is not in any sense 'determined' *by* $s(t_0)$ and the laws. As Physical Indeterminism does not entail the indeterminateness of the past/future of an event, it follows that it does not alone justify the claim that the universe 'branches', just insofar as nomic indeterminism is consistent with linear time. Given this, in order to jump from the world being Physical Indeterministic to the world having a branching structure, one must employ a non-trivial link between the two concepts. Moreover, if NBB is to be vindicated, then there must either be reason to think that the world is past-determinisitc and future-indeterministic, or the indeterminism-indeterminateness link must be employed selectively—future-indeterminism may entail branching, but past-indeterminism may not. I shall argue that neither of these are promising options.[26]

[26]This is dependent on the assumption that there are laws of nature. It may thus be objected that since BST does not require laws of nature, this point is irrelevant to BST. However, my point is not that for a world to be BST-indeterministic it must also be Physically Indeterministic. Rather, I am concerned with what it would take to justify the claim that the world has a (one-way) branching structure, and my claim is that physics is the place to look for this, and physical theories concern themselves with nomic indeterminism

### 4.3.1 The relevance of time reversal invariance

A theory is time reversal invariant (TRI) iff there is a time reversal operation that takes each model of the theory to a model of the theory. Intuitively, this means that if some sequence of states is allowed some theory, $T$, then the temporally inverted sequence of time-reversed states (as determined by the relevant operation[27]) is also allowed by $T$. In *The Physics of Time-Asymmetry*, Paul Davies declares that "all known laws of physics are invariant under time reversal" (Davies, 1977, p. 26). This is both a common and contentious claim. Indeed, the nature of the time reversal operation itself is subject to much scrutiny in the recent literature.[28] However, the claim that, given certain assumptions, the fundamental laws of physics are TRI is relatively uncontroversial. For instance, Dieter Zeh clarifies that "[a]ll known *fundamental* laws of Nature are symmetric under time reversal *after compensation by an appropriate symmetry transformation*, thus defining a combined symmetry, say $\hat{T}$. For example, $\hat{T} = CPT$ in particle physics, while $\hat{T} = \{\mathbf{E}(\mathbf{r}), -\mathbf{B}(\mathbf{r})\}$ in classical electrodynamics" (Zeh, 2007, p. 4, second emphasis mine).

John Earman (1986) shows that on the assumption that a theory is TRI, it is future-(in)deterministic iff it is past-(in)deterministic—"time reversal invariance is sufficient to guarantee that [future] and [past] determinism stand or fall together" (Earman, 1986, p. 132).[29] Earman (2008) uses this point to criticise the future-only indeterminism of BST. In response to Earman, Placek and Belnap (2010) reiterate the state/event distinction, arguing that time reversal invariance is not relevant to NBB as it concerns 'states', understood as state-types, and thus places no restrictions on event-tokens. This is indeed the case. However, once more, there is reason to think that physical theories tell us something about the world, and that if a physical theory is TRI, then it tells us *more* than that for any evolution from one state-type $s_i$ to another state-type $s_f$ that it allows, there is another evolution from the state-type $s_f{}^*$ to the state-type $s_i{}^*$ that it allows (where $s^*$ is the time reverse of $s$). On the account of physical modality defended, TRI indeterministic laws tell us that if a state-token is of a state-type that according to the laws has an indeterministic future, then the state-token itself has a nomically indeterministic future, and crucially that any state-token of the *time-reversed* state-type has a nomically indeterministic past.

Furthermore, the symmetries and asymmetries of physical theories indicate the structure required by those theories. If one holds spacetime to have a $B$-theoretic structure, such that the two temporal directions are structurally distinct, then this is physically unmotivated if the relevant physics is TRI—it postulates a fundamental feature of time that the physics does not. Hence, given that fundamental physics is taken to be TRI, attempting to justify NBB by holding that time is anisotropic is physically unmotivated. Alternatively, one may

and not ontic indeterminism.

[27]Different theories have associated with them different time reversal operations. This is the subject of much recent literature concerning the non-trivial aspects of different time reversal operations. See Albert (2000) and the ensuing literature on this issue.

[28]For instance, see (Albert, 2000, ch. 1), Earman (2002), Malament (2004) and Arntzenius and Greaves (2009) for an illuminating recent discussion of the time reversal operation only in the context of classical electromagnetic theory.

[29]See (Earman, 1986, pp. 131-2) for details.

want to hold that time is unidirectional—that the universe unfolds in one time direction and not the other—which thus justifies NBB. However, this once more introduces metaphysical structure that is extraneous to TRI physics. TRI laws can be used to evolve a system in both time directions; given a particular state, we may evolve it according to the laws, or evolve its time-reverse according to the laws, giving us the evolution of the system in opposite time directions.[30] It follows from this that, for a TRI theory, time evolution is not unidirectional or solely future-directed.

However, it is also important to stress that the claim that NBB is physically unmotivated does not rest on the fundamental physics being TRI. Even if the fundamental laws were non-TRI it would not follow that they would support the future-indeterminate, past-determinate structure of BST. Given a state of a system, plus non-TRI laws that govern the future evolution of that system, the future may be generated straightforwardly by the laws, but not the past (this may however be achieved through making some sort of hypothesis about the past of the system). As such, if the laws are indeterministic, while the indeterminateness of the future may be supported by the laws (by employing the indeterminism-indeterminateness link), the required determinateness of the past would have to be put in by hand.

## 4.4 Time-Asymmetric Reasoning

In the previous subsection, I argued that insofar as Physical Indeterminism relates to branching, it does not appear to motivate the one-way branching dictated by NBB. Although NBB is a constitutive feature of BST, there are various points within the BST literature where independent motivation for NBB is offered, notably in (Belnap et al., 2001, §7A.2). I will now turn to this issue and argue that such reasoning displays what Huw Price (1996) terms a 'temporal double standard'. A temporal double standard is a line of reasoning applied to one temporal direction, but not to the other, that fallaciously 'produces' a time-asymmetric conclusion. I shall address two such instances of time-asymmetric reasoning.

The first instance concerns the alleged intuitiveness of forwards branching and counterintuitiveness of backwards branching.

> That starting with the concrete event that occurred yesterday morning there were incompatible possible events each of which might have transpired seems to us right; that more than one of these incompatible possible streams of events might have finished up in this very concrete situation seems to us wrong. (Belnap et al., 2001, p. 184)

> No sense can be made of two alternative possible evolutions, separate before some event and combining into a single evolution after it. (Placek and Belnap, 2010, §4.4)

The former passage conveys the counterintuitiveness of backwards branching, and the latter passage deems backwards branching nonsensical. Granted, it is *intuitive* that events can

[30] Again, the justification of particular time reversal operations is a controversial matter. However, in general such an operation is available.

have multiple possible futures and not multiple possible pasts, but a neutral analysis of the structure of time ought to award no significant privilege to such intuitions; after all, there is no good reason to think that such intuitions are directly informed by the underlying nature of reality. Although backwards branching is considered metaphysically problematic, as is suggested by the latter passage, the precise source of this problem is not clear. Given that forwards branching is not considered nonsensical or metaphysically problematic, then it appears that it is not the metaphysics of branching that is the problem. If one can accept the coherence of an event having modally incompatible outcomes, then without appeal to some important independent feature of time, one ought also to accept the coherence of an event having modally incompatible incomes.[31] However, it is not clear what this independent feature of time is.

A second such time asymmetry in reasoning is displayed in the use of nomic indeterminism to justify an open (indeterminate) future, and the the lack of such usage in the stipulation of a closed (determinate) past. Consider Belnap et al.'s example of the past history of a disc that was thrown at some point in the past, but is now at rest:

> Its future is then determined as continuing in the stopped state, at least for a while, whereas from its stopped state there is no inference to when in the past it was thrown. True, but irrelevant. No backward branching does not imply that this particular definition of "state" gives us information as to when the disc was thrown; it only implies that regardless of the poverty or richness of any concept of "state" that is brought into play, *there is a fact of the matter admitting no real alternatives*. The concrete event of the disc coming to a halt *has in its past a unique concrete event of its being thrown*—a fact that is *no less true for being absent from physical theories* cast in terms of systems and states. (Belnap et al., 2001, p. 185, my emphasis)

The problem here concerns the lack of such stipulations towards the future. The temptation is to hold that if we live in a nomically indeterministic universe, then the future is open. However, as I have argued, there is a perfectly reasonable sense in which a nomically indeterministic universe can result in an 'open past' for certain states. The message of this passage is that past indeterminism does not entail past indeterminateness—there can be a fact of the matter about the past, even if the laws and the present state do not determine this fact.[32] However, in order to support NBB, the same reasoning cannot be applied towards

[31] It should also be said that it is not just the brute time-asymmetric attitudes to forwards and backwards branching here that I find curious. I share the feeling that backwards branching is counterintuitive, but only insofar as I find forwards branching counterintuitive. My worry is that the *epistemic* openness of the future is what is lending credence to the supposed intuitiveness of forwards branching.

[32] Of course, if the laws governing the system (including the thrower of the disc, assuming there is one) described in the passage are deterministic, the system may then contain the relevant information to determine at what time the disc was thrown—this would then the problem of failing to quantify over the entire dynamically relevant state. We can ignore this by supposing that the example actually concerns indeterministic laws, and that there genuinely are multiple physically possible pasts for a state in which the disc is at rest.

the future; instead, it is assumed that future indeterminism supports an indeterminate, branching future, and justifies using branching time semantics. The asymmetric reasoning here comes in the form of denying the indeterminism-indeterminateness link only towards the past and not towards the future. If we can stipulate that, *contra* past indeterminism, the past is determinate, then unless some key time asymmetry is assumed, we can likewise stipulate that, *contra* future indeterminism, the future is also determinate. No justification is offered for breaking the indeterminism-indeterminateness link in one direction but not the other. Thus, the time-asymmetric branching structure that is produced is obtained using a time-asymmetric assumption. It is precisely this time-asymmetric selectivity in applying such principles that is problematic.

## 4.5 Justifying Time-Asymmetric Reasoning?

I have argued that the future-indeterminateness/past-determinateness of BST is extraneous to TRI physics, and not clearly motivated by non-TRI physics. I have also argued that basic intuitions given in favour of NBB are insubstantial. I'll now briefly turn to alternative issues that can be offered in favour of NBB. Müller (2009), for instance, argues that when looking at physical science to motivate indeterminism, one needs to look not just at the theories, but also scientific practice.

> [T]he evidence that science gives on the issue of determinism is much richer than what is encoded in scientific theories. Scientific practice and the use of the experimental method seem to me to provide stronger arguments in favor of indeterminism than any specific theory could provide. That practice relies on the possibility of freely choosing initial conditions for experiments. Experiment isn't just observation, but observation after intervention. And intervention is a modal notion: it means to realize a (real) possibility in a concrete situation in which the normal course of things would have been otherwise. (Müller, 2009, p. 54)

Although Müller is here concerned with justifying the modal nature of indeterminism, both issues cited—freedom to choose initial conditions, and the role of intervention in measurement—are understood as introducing modal time asymmetries. However, I am unconvinced that these issues offer strong reason to think that physics motivates the kind of branching structure consistent with NBB. First is the issue of the ability to freely choose initial, but not final, conditions for experiments. There is much to this claim—the phenomenon of feeling able to freely prepare systems, but not being able to 'postpare' them (control their final state) is certainly a real one. However, it is far from clear that the precise origin of this time asymmetry is the structure of time itself—for example, such time asymmetry is commonly explained in terms of the asymmetric imposition of constraints on boundary conditions of the universe.[33] Furthermore, experiments concerning weak values[34]

[33] *cf.* (Albert, 2000, ch. 4-6).
[34] *cf.* Aharonov et al. (1988).

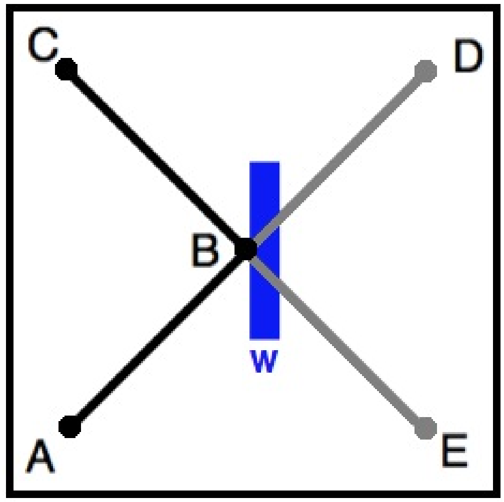



Figure 5: A ball takes the actual trajectory ABC, colliding with a wall, W, at B. The trajectories EB and BD are counterfactual trajectories consistent with the absence of W.

using the time-symmetric formalism of quantum mechanics[35] require one to both preselect and postselect the ensembles under consideration. Preselection consists in simply preparing the system in some state. Postselection involves concerning oneself with only that subset of the ensemble of systems that end up in some particular chosen state. Of course, this can only be done in practice with ensembles, unlike preselection, but one can nonetheless impose constraints on both the initial and final conditions of the systems one studies, and in the case of quantum mechanics, this has produced some genuinely interesting and non-trivial results (see Aharonov et al. (2010) for a summary).

Second is the issue of intervention. Belnap et al. (2001) and Placek and Belnap (2010) also make the point that the issue of intervention (*e.g.* by an experimenter when preparing a system, performing a measurement, *etc.*) is of particular importance to justifying NBB. However, as Reichenbach (1956) notes, the concept of intervention is not itself time-asymmetric in the required sense. Rather, such time asymmetry is *presupposed* in our consideration of intervention. Figure 5 illustrates a simplified version of Reichenbach's thought experiment (Reichenbach, 1956, pp. 43-45) in which a ball travels from point A, bounces off a wall at B and travels to point C. Reichenbach then asks "What would have happened if the [wall] had not been [present]?" The intuitive answer is that the ball would have continued towards a point D, beyond the wall. This answer preserves the initial trajectory AB, but replaces BC with BD. However, Reichenbach then considers an alternative history of the ball that preserves the trajectory BC, but replaces AB with an alternative trajectory EB, where E is a point behind the wall, and reconsiders the question.

> [T]he question cannot be answered unless a further specification is given. Either one of the processes [ABD or EBC] could then have happened. The conditional

[35] *cf.* Aharonov et al. (1964).

> contrary to fact "If the [wall] had not hit the ball, then..." is ambiguous; the blank in it cannot be filled in before we say whether we want to keep the part AB or the part BC of the ball's path unchanged. But seen from the event B, these parts represent the past and the future, respectively. When we say that [the ball hitting the wall] changes the future path of the ball, our statement presupposes the tacit antecedent, "if we assume the past to remain unchanged". No wonder that acts of intervention change only the future, and do not change the past; the term "intervention" is defined by the condition that the past be unchanged. (Reichenbach, 1956, pp. 44-45)

The time asymmetry that is intended to justify NBB—that an act of intervention, such as a measurement, affects the future and not the past—is question-begging. If one relaxes the presupposition that interventions leave the past 'fixed', then no such asymmetry is produced. Once more, the burden is shifted to some other unspecified time asymmetry. In the absence of such a time asymmetry, making such stipulations towards the past and not towards the future once again constitutes a temporal double standard, and as such fails to provide independent justification of NBB.[36]

I am not denying that there are phenomenological time asymmetries associated with the ability to prepare systems, and to intervene on systems so as to influence future and not past states. However, I am questioning the origin and significance of these time asymmetries, and arguing that there is insufficient reason to think that they constitute, or provide evidence of the existence of, a time-asymmetric modal structure of the world. Logically there is no problem with preparing and postparing a system, and in practice this can be done with ensembles. Likewise, no time asymmetry logically follows from the concept of intervention. Such seeming time asymmetries underdetermine their origin. The origin(s) of the thermodynamic time asymmetry, the electromagnetic time asymmetry, the time asymmetry of agency, *etc.*, is an interesting but open question, and it is far from clear that they are ultimately traceable back to some basic asymmetry in the structure of time, especially one that would be relevant to NBB.[37]

## 4.6 Reflections on $B$-Theoretic Branching

To summarise the discussion of this section, I have argued that: it is perfectly meaningful for the past to be indeterministic, and if this is understood modally, it is incompatible with BST due to NBB; we should look to physics, not intuitions, for information about the

[36] Lewis (1979) offers such an independent justification for the time asymmetry of counterfactual dependence in terms of his 'asymmetry of miracles', but Elga (2001) demonstrates that this fails for simple cases. Elga's argument concerns only statistical mechanical processes, but demonstrates that Lewis' purported justification for the time asymmetry rests on the (time-asymmetric) assumption that time is unidirectional (*cf.* Farr and Reutlinger (2011)).

[37] Indeed, a popular approach is to trace the physical time asymmetries back to a contingent cosmological feature of the universe—that it is has a low entropy constraint at one temporal end—rather than to some fundamental structural asymmetry of time. See, for instance, Davies (1977), Hawking (1989), Price (1996), Albert (2000), Zeh (2007).

modal structure of the world, and there is no good reason to think that physical theories can lend credence to a time-asymmetric branching structure consistent with NBB; proposed independent justification for the time asymmetry of NBB either presupposes the relevant time asymmetry, or is inconclusive.

It is an open question as to whether the timelike dimension of spacetime features some basic structural asymmetry to distinguish the past and future directions in a way sufficient to ground something like a one-way branching modal structure. This is one of the most significant philosophical problem concerning time.[38] It is reasonable to at least consider the openness of the past as well as the openness of the future, and not to simply rule out the coherence of the former.[39]

# 5 In Conclusion

I have considered two elements of different branching spacetime theories—one $A$-theoretic, and one $B$-theoretic—and considered the metaphysical implications of these, and the problems they entail for the theories containing them. McCall's branch attrition either requires or constitutes a dynamic past/present/future distinction, and this requires a model with at least two temporal dimensions. Modeling it as such helps to clarify apparent ambiguities in his presentation, but results in severing the conceptual link between branch attrition and the flow of time. NBB, I have argued, prohibits BST from modeling past indeterminism, and ascribes a physically unwarranted time-asymmetric modal structure to the universe. Consideration of the time-symmetric nature of fundamental physical theories suggests that it is at least worth taking seriously a time-symmetric account of indeterminism, and considering a $C$-theoretic branching time model that provides analogous semantics for future and past indeterminism. However, whether the commitment to supertime is a fatal extravagance of $A$-theoretic models, and whether NBB is justifiable, are open questions. I hope this paper has shed some light on the potential metaphysical commitments of branching spacetime theories and their relation to the metaphysics of time.

[38]For instance, Price (1996) argues that the a proper appreciation of the time-symmetry of microphysics, and of the possibility that time lacks a direction, leads to promising new approaches to various old problems in both philosophy and physics, from the philosophical analysis of causation to the interpretation of quantum mechanics. Conversely, Maudlin (2007) argues that the unidirectional passage of time is too overlooked by philosophers, and is of crucial relevance to many basic problems in philosophy and physics.

[39]Indeed, discussion of backwards branching does prompt the intuition that, in such cases, an *actual* past is perfectly intelligible in a way that an actual future is perhaps not. The temptation of using the concept of an 'actual' past amongst possible pasts is interesting as it lends credence to the unfashionable doctrine of the 'thin red line' (TRL). As far as I know, this type of approach has not been used to distinguish actual from possible *pasts*, as current TRL theories are modeled more-or-less within the BST framework, and thus adhere to NBB.

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